

On the rotationally driven pevatron in the centre of the Milky Way.

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ABSTRACT

Based on the collective linear and nonlinear processes in a magnetized plasma surrounding the black hole at the galactic center (GC), an acceleration mechanism is proposed to explain the recent detection/discovery of PeV protons. In a two stage process, the gravitation energy is first converted to the electrical energy in fast growing Langmuir waves, and then the electrical energy is transformed to the particle kinetic energy through Landau damping of waves. It is shown that, for the characteristics parameters of GC plasma, proton energy can be boosted upto 5PeV.

Subject headings: (ISM:) cosmic rays; The Galaxy; acceleration of particles

1. Introduction

Recent detection of PeV protons in the Galactic Centre (GC) by the High Energy Stereoscopic System (HESS)(Abramowski et al. 2016) has sharpened the focus on a major quest in high energy astrophysics- how do elementary particles get driven to such enormous energies! It is, perhaps, obvious that the preponderant gravitational energy in the neighborhood may be the ultimate power source but charting the chain of processes that channel the gravitational into particle kinetic energy constitutes the challenge and the main objective of this paper.

Let us begin with a short summary of the phenomenology. The analysis of Very High energy (VHE) γ -rays, observed in the same region as the PeV protons, shows a strong correlation between the γ -ray distribution and location of giant gas-rich complexes implying that the diffuse emission might have a hadronic origin (Abramowski et al. 2016). The HESS collaboration, for example, has

observed the diffuse VHE emission from the centre of Sagittarius (Sgr) A*. The spectrum of γ -rays (with energies up to tens of TeV) follow a power law with a photon index ~ 2.3 , and as such, is a first detection of VHE photons originating in the hadronic pp interactions. It is, then, argued by the authors of Ref. (Abramowski et al. 2016) that the parent protons, producing γ -rays, must have energies of the order of 1PeV. The authors also suggest that a possible candidate for the observed PeV protons could be Sgr A east. Although more effort is needed to interpret HESS data, the authors have come to the initial conclusion that the acceleration rate might be of the order of $10^{37-38} \text{ ergs s}^{-1}$, which in turn suggests that in the past the bolometric luminosity of Sgr A* might have been by two or three orders of magnitude bigger than its currently estimated value.

Before discussing our acceleration model, it is pertinent to point out some alternative candidates like the shock acceleration-possibly via

the Fermi acceleration at the stand-off accretion shock (Webb & Bogdan 1987) or in the termination shocks of winds (Lemoine et al. 2015) seem to be quite inadequate for catapulting particles to such high energies (Abramowski et al. 2016; Malkov & Drury 2001). Our model scenario, in which a series of well-defined physical processes conspire to accelerate protons to the observed/inferred PeV energies, unfolds via the following two essential steps:

1) First the centrifugal force, acting differentially on the plasma particles (on different species like electrons and protons, and different relativistic γ for the same species), creates conditions in which fast growing Langmuir waves can be, parametrically, excited. This rapid conversion of gravitational energy into electrical energy is the first defining step of the model (Osmanov 2008; Machabeli et al. 2005).

2) Through a somewhat involved process, described in the Methods section, these vastly amplified gravitationally driven Langmuir waves transfer the electrical energy to particle kinetic energy through Landau damping. The Langmuir waves are sustained by the bulk plasma, and therefore constitute a huge reservoir of electrical energy. The Landau damping, however, is much more selective, operating, preferentially on the most energetic particles, imparting them even greater energy. This is the second major step of the model -converting the gravitationally generated electrical energy to kinetic energy of particles.

The two-step process of energy transfer leading to enormous acceleration of particles is most efficient when the “impedances” match- when the rate of growth, and of Landau ‘damping of Langmuir waves are comparable. The workability and efficiency of this overall mechanism has already been demonstrated in a set of papers relevant to a variety of astrophysical settings varying from the magnetospheres of the neutron stars (crab-like pulsars, newly born millisecond stars-) to the vicinity of Active Galactic Nuclei (AGN) (Osmanov et al. 2015, 2014; Mahajan et al. 2013).

It has been amply shown in the above references that the Langmuir-Landau-Centrifugal Drive (LLCD) is a phenomenally efficient plasma mechanism that can accelerate particles to energies 10^{18} eV in millisecond newly born pulsars (Osmanov et al. 2015; Mahajan et al. 2013), and

to 10^{21} eV in AGN (Osmanov et al. 2014).

After outlining the theoretical model, we work out, in Sec.2, the details of the particle acceleration mechanism for typical parameters of the galactic centre. In Sec. 3, we summarize our results.

2. Theoretical Framework and Particle Acceleration

We will begin by giving a brief outline of the theory of centrifugally excited Langmuir waves in a relativistic electron-proton plasma. We will then apply this theory to work out an acceleration pathway to PEV energies.

2.1. Theoretical model

One begins with the linearized set of equations (Osmanov et al. 2015), composed of the Euler equation

$$\frac{\partial p_\beta}{\partial t} + ikv_{\beta 0}p_\beta = v_{\beta 0}\Omega^2 r_\beta p_\beta + \frac{e_\beta}{m_\beta}E, \quad (1)$$

the continuity equation

$$\frac{\partial n_\beta}{\partial t} + ikv_{\beta 0}n_\beta + ikn_{\beta 0}v_\beta = 0 \quad (2)$$

and the Poisson equation

$$ikE = 4\pi \sum_\beta n_{\beta 0}e_\beta, \quad (3)$$

where β is the species index, p_β is the first order dimensionless momentum ($p_\beta \rightarrow p_\beta/m_\beta$), $v_{\beta 0}(t) \approx c \cos(\Omega t + \phi_\beta)$ is the zeroth order velocity and $r_\beta(t) \approx \frac{c}{\Omega} \sin(\Omega t + \phi_\beta)$ is the radial coordinate (Osmanov et al. 2014), e_β is the particle’s charge and n_β and $n_{\beta 0}$ are the perturbed and unperturbed Fourier components of the number density. The first term in the righthand side of Eq. (1) is the relativistic analogue of the centrifugal force, which, as we have already discussed in the previous section acts on particles with different radial coordinates and leads to the excitation of the unstable electrostatic waves.

A little extra detail may be helpful. In an idealized version, considering plasma to consist of two streams of protons and electrons, one can show

that the centrifugally amplified Langmuir waves grow at the rate (Osmanov et al. 2014)

$$\Gamma = \frac{\sqrt{3}}{2} \left(\frac{\omega_e \omega_p^2}{2} \right)^{\frac{1}{3}} J_\mu(b)^{\frac{2}{3}}, \quad (4)$$

where $\omega_{e,p} \equiv \sqrt{4\pi e^2 n_{e,p}/m_{e,p} \gamma_{e,p}^3}$ and $\gamma_{e,p}$ are the relativistic plasma frequency and the Lorentz factor for the two streams of particles, $b = \frac{2ck}{\Omega} \sin \phi_-$, k is the wave vector, $\phi_{e,p}$ are the phases of the corresponding particles, $2\phi_- = \phi_p - \phi_e$, $J_\mu(x)$ is the Bessel function of the first kind and $\mu = \omega_e/\Omega$.

2.2. Acceleration of protons

To make an estimate of the (relatively strong) magnetic field in neighborhood surrounding the GC black hole, we note that the particle acceleration rates $\sim 10^{37-38} \text{erg s}^{-1}$, quoted in (Abramowski et al. 2016), suggest that in the past the luminosity of SgrA* should have been two or three orders of magnitude more than its currently believed value $\sim 5 \times 10^{35} \text{erg s}^{-1}$. Assuming equipartition of energy, one readily estimates the local magnetic field strength to be (Osmanov et al. 2007),

$$B \approx \sqrt{\frac{2L}{r^2 c}} \approx 15.4 \times \left(\frac{L}{5 \times 10^{38} \text{erg/s}} \right)^{1/2} \times \frac{10 R_S}{r} G, \quad (5)$$

where L is the bolometric luminosity of SgrA*, $R_S = 2GM/c^2$ is the Schwarzschild radius of the black hole, $M \approx 4 \times 10^6 M_\odot$ is its mass (Gillessen et al. 2009) and $M_\odot \approx 2 \times 10^{33} \text{g}$ is the solar mass. It is straightforward to check that the Larmor radius of electrons and protons is by many orders of magnitude less than the Schwarzschild radius implying that the surrounding plasma is magnetized, and the particles will, mostly, follow the field lines. Analyzing the radio emission of Sgr A it has been revealed that the mentioned super-massive black hole is rotating (Enslin 2003). On the other hand, since the rotating black hole is supposed to be spinning with the angular velocity (Shapiro & Teukolsky 2004),

$$\Omega \approx \frac{ac^3}{GM} \approx 2.5 \times 10^{-3} \frac{a}{0.1} \text{rad s}^{-1}, \quad (6)$$

where $0 \leq a \leq 1$ is a dimensionless parameter characterizing the rate of rotation, the frozen-in

condition of plasmas will, inevitably, lead to direct centrifugal acceleration. The acceleration becomes extremely efficient close to the so called the light cylinder (LC) surface defined by $R_{lc} \equiv c/\Omega$; it is a hypothetical boundary where the linear velocity of rotation exactly equals the speed of light.

In the present model, magnetic field lines are assumed to be almost straight, and the centrifugal drive continues to accelerate particles until the plasma energy density exceeds that of the magnetic field. The acceleration process, thus, terminates when a particle with mass m achieves a Lorentz factor (Osmanov et al. 2014),

$$\begin{aligned} \gamma_{dir} &\approx \frac{1}{c} \left(\frac{e^2 L}{2m} \right)^{1/3} \approx \\ &\approx 1.3 \times 10^5 \left(\frac{L}{5 \times 10^{38} \text{erg/s}} \right)^{1/3} \times \left(\frac{m_e}{m} \right)^{1/3}, \quad (7) \end{aligned}$$

where $m_e \approx 9.1 \times 10^{-28} \text{g}$ is the electron mass. Thus, the direct centrifugally acceleration can propel protons to a maximum Lorentz factor of the order of 10^4 . This energy, is far below, the proton energies detected by HESS. But such energetic protons form the faster of the proton component in of the electron- proton plasma in the accretion disc at the GC, and comprise the class of particles most effectively accelerated further by the Landau damping of the Langmuir waves, a collective mode of oscillation of the bulk plasmas. Both the single particle, and collective mechanisms act in synch to boost the proton energies to PeVs.

For a plasma with a wide range of electron and proton energies (including protons with $\gamma_p \sim 10^3$) one can show that the rate of growth $\Gamma \sim 8.8 \times 10^{-4} \text{s}^{-1}$ is twice as large as the rotation frequency $\Omega/2\pi$; the latter sets the kinematic timescale. The centrifugally excited Langmuir modes, therefore, are very efficient in extracting rotational energy.

The linear build up of the electrostatic energy is further compounded by a nonlinear mechanism. An electrostatic wave, with a relatively small amplitude, generates a high frequency pressure that pushes out the particles from the perturbed area, creating low density regions called the caverns (Zakharov 1972). The waves penetrate these areas, increase the high frequency pressure, intensify the process even more and result in what has been termed the Langmuir collapse.

Since the density perturbation is much less than the unperturbed value, n_0 , the corresponding change in frequency of plasmons will be negligible as well, $\delta\omega \ll \omega$. Therefore, the energy of plasmons (the electrostatic energy) is constant

$$\int d\mathbf{r} |E|^2 = \text{const}, \quad (8)$$

where E is the electrostatic field.

The perturbation of density in cavities lead to the high frequency fluctuation of pressure, $P_{hf} \approx -E^2\delta n/(24\pi k^2\lambda_D^2 n_0)$ (Artsimovich & Sagdeev 1979), which scales as $P_{hf} \propto E^2$, where δn is the electron density perturbation, $\lambda_D \equiv \sqrt{k_B T_e/(4\pi n_0 e^2)}$ is the Debye length scale, $k_B \approx 1.38 \times 10^{-16}$ erg K⁻¹ is the Boltzmann constant, and T_e is the electron temperature.

From Eq. (8) it is evident that $P_{hf} \propto 1/l^q$, where q denotes the number of relevant spatial dimensions. It is clear that the high frequency pressure can overcome the thermal pressure, $P_{th} = k_B T \delta n \propto 1/l^2$ only for the three dimensional geometry (Osmanov et al. 2014). We have taken into account that in cavities the plasmons have kinetic and potential energies of the same orders of magnitude, $k^2\lambda_D^2 \sim |\delta n|/n_0$, leading to the behaviour $\delta n \propto k^2 \propto 1/l^2$.

We deduce from the physics summarized in the preceding paragraph that inside the magnetosphere, where the plasma particles follow the magnetic field lines implying an essentially one-dimensional ($q = 1$) kinematics, the Langmuir collapse is prohibited.

Outside the LC, however, the plasma processes are no longer defined by rotation but predominantly by accretion. In this region the plasma density is approximately given by (Osmanov et al. 2014)

$$n = \frac{L}{4\eta\pi m_p c^2 v R_{lc}^2} \approx 6.3 \times 10^4 \times \left(\frac{L}{5 \times 10^{38} \text{ erg/s}} \right) \text{ cm}^{-3}, \quad (9)$$

where $v = \sqrt{2GM/R_{lc}}$ is the velocity of the accreting matter close to the LC zone; we have assumed that almost 10% of the rest energy of the accreting matter transforms to radiation ($\eta = 0.1$). For the estimated number density, the plasma frequency exceeds the cyclotron frequency: the particles outside the LC, therefore, are not bound by the magnetic field (the dynamics

is 3D), and a collapse might occur.

By combining the relations $|E|^2 \sim 1/l^3$ and $\delta n \sim 1/l^2$, one can show that the time behavior of the induced electrostatic field, and the length scale of the cavern are given by (Zakharov 1972)

$$|E| \approx |E_0| \frac{t_0}{t_0 - t} \quad (10)$$

$$l \approx l_0 \left(\frac{t_0}{t_0 - t} \right)^{-2/3}, \quad (11)$$

where t_0 is the collapse time scale, $E_0 \approx 4\pi n e \Delta r$ is the initial electrostatic field and $\Delta r \approx R_{lc}/(2\gamma)$ is a length scale close to LC where the acceleration occurs (Osmanov et al. 2014). We find from Eq. (10) that the Langmuir collapse boosts up the initial electric field by the factor $(\Delta r/l_c)^{3/2}$, where $l_c \approx 2\pi\lambda_D$ is the dissipation length scale; the collapse is, finally, terminated by means of the Landau damping. Through Landau damping, The highly amplified electrostatic energy ($\epsilon_p \approx E^2/(8\pi n)$),

$$\begin{aligned} \epsilon_p (\text{eV}) &\approx 5.3 \times 10^{15} \times \frac{\eta}{0.1} \times \left(\frac{a}{0.1} \right)^{1/2} \times \\ &\times \left(\frac{T_e}{10^5} \right)^{-3/2} \times \left(\frac{10^3}{\gamma_p} \right)^5 \times \left(\frac{L}{5 \times 10^{38} \text{ erg/s}} \right)^{5/2}, \end{aligned} \quad (12)$$

is, finally, deposited on protons through Landau damping. One has to note that for optimal transfer of energy to protons, the rate of generation of Langmuir waves (measured by , the instability growth rate) and the Landau damping rate, $\Gamma_{LD} \approx \omega/\gamma_e^{3/2}$, should be comparable (Mahajan et al. 2013), where $\omega = \sqrt{4\pi e^2 n_p/m_p}$. One can show straightforwardly that for not violating the aforementioned condition, the minimum value for γ_p is approximately 500, leading to the highest achievable energies of the order of 170 PeV.

It is evident from Eq. (12) that if one considers protons with the initial Lorentz factors of the order of 10^3 , they can be efficiently accelerated by the LLCD mechanism up to energies recently detected by the HESS telescope.

A comment on a possible limit on maximum energies accessible to ultra-high energy protons, imposed through interactions with soft photons (Inverse Compton - IC), is in order. Since the

associated cooling time, $t_{KN} = \epsilon_p / P_{KN}$, where

$$P_{KN} \approx \pi r_p^2 m^2 c^5 n_{ph}(\epsilon_{ph}) \left| \ln(4e\epsilon/m^2 c^4) - 11/6 \right|, \quad (13)$$

is the power emitted by proton per second in the Klein-Nishina regime (Blumenthal & Gould 1970), $r_p = e^2/m_p c^2$, $n_{ph} \approx L/(R_{lc}^2 c \epsilon_{ph})$ and $\epsilon_{ph} \sim 1\text{GeV}$, is of the order of 10^{22}sec , IC mechanism is not efficient in cooling ultra-high energy particles.

Unlike IC (operative but not efficient), the curvature radiation does not exist at all. It has already been shown that the curvature driven current leads to generation of the toroidal magnetic field twisting the field lines so that outside the LC the particles follow straight trajectories. Therefore, outside the magnetosphere, where the collapse actually takes place, it is not influenced by the curvature energy losses.

3. Summary

We will now describe the results as well as some detailed description of the physics of acceleration when the LLCD mechanism is applied to the parameters of an electron-proton plasma medium, surrounding the black hole in the GC. Of course, the basic motivation is to explain the origin of PeV protons, detected, recently, by the HESS collaboration.

Although, the relatively strong magnetic fields could provide a direct centrifugal acceleration to particles (terminated, eventually, by inverse Compton scattering), the most efficient mode of drawing energy from the gravitational field comes, somewhat naturally, through the exploitation of the collective phenomena in a plasma that allow the building and sustenance of enormous electric fields (and large density fluctuations) in Langmuir or plasma waves.

Let us now capture the essence of the working of LLCD in the GC plasma:

1) The free-energy available in the differential response of different plasma particles to the gravitational field, parametrically, drives a fastly growing linear instability in Langmuir waves

2) In the AGN environment, the growth of wave energy is further enhanced, nonlinearly, by what is known as Langmuir collapse. The physics of Langmuir collapse is such that starting from moderate

amplitudes, immense concentration of field energy (accompanied by the creation of density cavities) results via what could be called an explosive nonlinear instability. The nonlinearly generated high frequency component of pressure, further, pushes out the particles from the cavities; the positive feedback, in turn, amplifies the energy of the electrostatic waves.

3) This immense concentration of electrical energy (and density) is terminated through Landau damping- the resonant feeding of particle kinetic energy at the cost of the field energy. The nonlinear Langmuir collapse, by decreasing the length scales of the caverns, makes the Landau damping process extremely efficient. At the end of the day, the gravitational energy, through the linear and nonlinear build up of Plasma waves and their Landau dissipation, is efficiently transferred to protons; we show that for the following set of parameters: $T_e = 10^5\text{K}$, $a = \eta = 0.1$, $\gamma_p = 10^3$, $L = 5 \times 10^{38}\text{erg/s}$, the particles might reach energies of the order of 5PeV. The minimum value of $\gamma_p = 500$ when the necessary condition, $\Gamma \sim \Gamma_{LD}$ still holds, leads to the maximum proton energy of the order of 170PeV.

Acknowledgments

The research of ZO was supported by Shota Rustaveli National Science Foundation DI-2016-14; The work of SM was, in part, supported by USDOE Contract No.DE- FG 03-96ER-54366 and the research of GM was partially supported by Shota Rustaveli National Science Foundation FR/516/6-300/14.

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